Small-Scale Locomotion, Intelligent Cooperation, and Energy-Efficient Computation: A Concept for Cooperating Heterogeneous Biomorphic Explorers

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In this presentation, we describe a concept for teams of heterogeneous biomorphic explorers (or micro-robots) that can cooperate to perform applications in space exploration. Of course, developing a complete, fully functional micro-robot system (where each robot is on the order of a 5cm cube in size, or smaller) that is optimized for performance in real-world applications is a significant challenge. Such a project would require the thorough analysis and development of many component subsystems, including actuation, locomotion, micro-transmitter communication, electronics, power supplies, power management, cooperative control behaviors, and small-scale sensors such as LIDAR and miniature cameras. To date, few systems have even begun to address all of these issues that would lead to a robust, non-toy team of micro-robots that can operate reliably in the real world. A key reason why it has been difficult to build non-toy micro-robot systems is that the scientific challenges of integrating subsystems that meet a complex set of constraints have not been adequately addressed. We explore these issues by examining three principal components of a cooperative biomorphic system and how advances in each area can be integrated toward the development of a fully functional micro-robot system. The three areas of focus are: (1) *small-scale locomotion,* (2) *intelligent cooperative behavior,* and (3) *partitioned energy-efficient computation*.

In the *small-scale locomotion* area, the concept calls for individual robots of the cooperative system to be multi-legged vehicles designed using shape memory alloy actuation. The conceptual design permits an integral system where the body, legs, and their corresponding actuators are all molded into a single structural and functional piece, thus radically reducing parts count and fabrication costs while increasing robustness. The robot can have additional front and rear connections for a spine linkage to permit the hard connection to other individual robots. These spine linkages are the primary physical mechanism enabling reconfigurability of the collective system. This ability of the robots to connect together and perform a task is a crucial feature of the cooperative ability, which exceeds the individual ability of any single robot by itself.

In the *intelligent cooperative behavior* area, the concept focuses on the development of advanced decision algorithms that enable robots to determine when, where, and how to pool their capabilities and reconfigure themselves in response to navigation challenges or changing mission requirements. Novel cooperative control mechanisms for the system are based upon our earlier successes in developing fault tolerant, adaptive action selection among multiple heterogeneous robot team members. The approach involves the use of our ALLIANCE architecture---a behavior-based, distributed control technique that has been proven to enable robot team members to automatically select appropriate actions even in the midst of sensor and actuator uncertainties, robot failures, and mission changes in a dynamic and unfamiliar environment. Of course, the challenge of achieving cooperation in teams of micro-sized robots is to scale the control algorithms to meet the strict computational size and power constraints of small biomorphic explorers. The concept incorporates an approach to developing a fundamental scientific understanding of the basic requirements of cooperation, so that algorithms for any given computational and power constraints can be successfully developed. This new understanding will enable the development of algorithms for cooperative behavior control for a wide variety of biomorphic explorers.

In the *partitioned energy-efficient computation* area, the concept focuses on the state-of-the-art development of a low power consumption computational architecture that allows the implementation of cooperative micro-robot behaviors. This computational architecture could provide an alternative to the standard embedded micro-controller and general-purpose processor technologies currently used for larger robot systems. This architecture must meet the strict size and power constraints of small fielded systems that have no support power grid. The conceptual approach is to partition functions – such as locomotion, sensing, communication, and decision making – according to synchronous digital, asynchronous digital, and analog computation suitability. The partitioning is implemented based upon a biological model that segments the behaviors into cognitive, sensory, and motor functions. This type of partitioning should enable energy efficient cooperative behavior computations onboard biomorphic explorers with limited power supplies, thus providing capabilities not possible with existing systems.